Waves, Bubbles, Noise, and Underwater Communications

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LONG-TERM GOALS

The long term goals are to (1) understand the role of wave-induced bubbles in the upper ocean boundary layer on the performance of underwater communications systems and ambient noise generation, (2) study the implications of focusing by surface gravity waves on Doppler sonar and acoustic communications systems in shallow and very shallow water, and (3) study the performance of acoustic vector sensors in very shallow water.

OBJECTIVES

The objectives of the research are to address the questions in the areas identified below.

1. Bubbles and ambient noise. What is the physical origin of wave-driven, oceanic ambient noise? The specific goals over the past 12 months have been to identify the physical mechanism responsible for the acoustic excitation of newly formed bubbles and analyze a dataset of surface images taken at the Martha's Vineyard Coastal Observatory for whitecap coverage and its dependence on environmental conditions.

2. The focusing of sound by surface gravity waves.Shoaling waves create focal regions in surface-scattered sound in the very near shore region, which impact the performance of underwater communications systems and acoustic Doppler sonars. The objective is to understand and model the intensity, phase, and Doppler shift of the focal regions. Efforts over the past 12 months have centered on high-frequency scale model laboratory experiments of forward scattering from waves.

3. Study the performance of acoustic vector sensors in very shallow water. The specific objective has been to prepare and deploy an array of vector sensors in the surf zone to test mounting and acquisition systems for a full deployment in March, 2008.

APPROACH

The overall approach is to combine instrument development with laboratory and field studies to study bubble noise, surface scattering, white capping, and vector sensor deployment in the surf zone. The data obtained is analyzed and, where appropriate, compared with models and theory to increase our understanding of these processes.

The bubble and surface scattering work has been supported with three experimental programs. Bubble measurements have been made in the laboratory with hydrophones and high speed imaging techniques

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14. ABSTRACT
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to study the details of acoustical excitation and damping of bubbles fragmenting in fluid turbulence and released from a nozzle. Surface scattering has been studied in the laboratory with high frequency (300 kHz) transducers and small-scale surface waves created in a laboratory flume. The laboratory measurements permit a high degree of control over wave shape and a precise reconciliation between the measured forward scattering and model predictions. The third experiment is a major field deployment involving SIO, WHOI, The University of Rhode Island, and the Institute of Ocean Sciences, BC, that was staged at the Air-Sea Interaction Tower at WHOI to study surface processes and acoustic communications (SPACE07). In addition to these programs, archived data from an earlier experiment at WHOI (SPACE02) and bubbles experiments performed in the previous performance period have been analyzed.

WORK COMPLETED

1. **Bubbles and Ambient Noise**. Experiments were done in 2005 and 2006 to study the noise radiated by bubbles fragmenting in fluid turbulence. Approximately 2 mm radius bubbles were created and allowed to rise into the turbulent flow created by opposing fan-shaped fluid jets. The fragmentation processes was studied with a high-speed camera and synchronized ITC 6050C hydrophone. An initial analysis of this data was presented in the performance report for FY 05-06. Further study of the data has provided clues about the acoustic excitation and damping mechanisms, and these are reported here. Motivated by this analysis, an additional experiment has been conducted to study the acoustic emissions of bubbles released from a nozzle. The results of this experiment are detailed below.

2. **Surface Gravity Wave Focusing**. Two experiments were performed to support this effort. The first was a scale model experiment in the glass-walled flume in the Hydraulics Facility at SIO. This is a 30 m long flume with a hydraulic paddle at one end and a beach to absorb wave energy at the other. The channel is approximately 0.6 m deep and 1 m wide. Two broad-band, high frequency ITC transducers (ITC 1089D) were positioned approximately 1 m apart, beneath paddle-generated surface waves. Broad-band, time limited pulses were transmitted, forward-scattered by the surface and recorded. The transducers were positioned carefully to avoid contamination of the surface-scattered signal by reverberation from the tank walls and floor. The wave profile was measured with rapid-response wire wave gauges.

A second experiment for this topic and the bubbles and ambient noise studies was SPACE07. This was a major field deployment to study surface processes and acoustic communications. A significant fraction of laboratory resources went into preparing for this experiment, which included the fabrication of an array of 11 m capacitive wave gauges to measure the surface wave field, a hydrophone array to monitor ambient noise on the sea floor, and a surface-monitoring video system to capture white cap coverage and study wave breaking dynamics. In addition, a surface-following frame with a high speed video camera, an array of three dimensional Doppler Sonar velocity meters, a conductivity cell and a micro-CTD to study turbulence and air entrainment by whitecaps was refurburshed, along with 2 bottom-mounted acoustic wave gauges. SIO provided the diving support for the experiment, which included diver training and arranging for a UNOLS Nitrox van from the University of Rhode Island. Unfortunately, this experiment was cancelled a few days before deployment because of permitting issues and no data was obtained.

Surface image data from an earlier deployment, SPACE02, has been analysed to study the relationship between whitecap coverage and wind and wave conditions. This effort involved the computer analysis of over 100,000 images of wave breaking from the air-sea interaction tower at WHOI over a broad range of wind-forcing, wave, and current conditions. The results of this analysis, undertaken by Adrian Calahan as part of his PhD thesis, are presented below.

3. **Vector Sensor Studies**. A preliminary deployment of a Wilcoxon vector sensor has been completed. Vector sensors are particularly sensitive to flow noise, and a mounting system designed in collaboration with the vector sensor manufacturer was delpoyed and tested. The results of this study will be used to design a full array deployment in March, 2008, and are documented below.

RESULTS

1. **Bubbles and Ambient Noise Experiments.** There are two main results that have come from these studies over the past 12 months. The first is that the mechanism driving acoustic excitation in fragmenting bubbles – an important bubble formation process in breaking waves – appears to be associated with the neck of air joining the bubbles immediately prior to fragmentation. This is an important result as it explains the great variability seen in radiation strength from one fragmentation event to another and points the way to explaining the magnitude of the radiation. The implication is that bubble noise is driven by the conversion of free surface tension energy in the bubble neck into breathing mode oscillations. The strongest evidence for this conclusion for fragmenting bubbles is shown in Figure 1.

Figure 1. The plot shows the breathing mode energies (in Joules) of pairs of bubbles created by a single event. About 500 fresh and salt water events are plotted. The strong correlation between energies over three orders of magnitude suggests an excitation mechanism common to both bubbles.

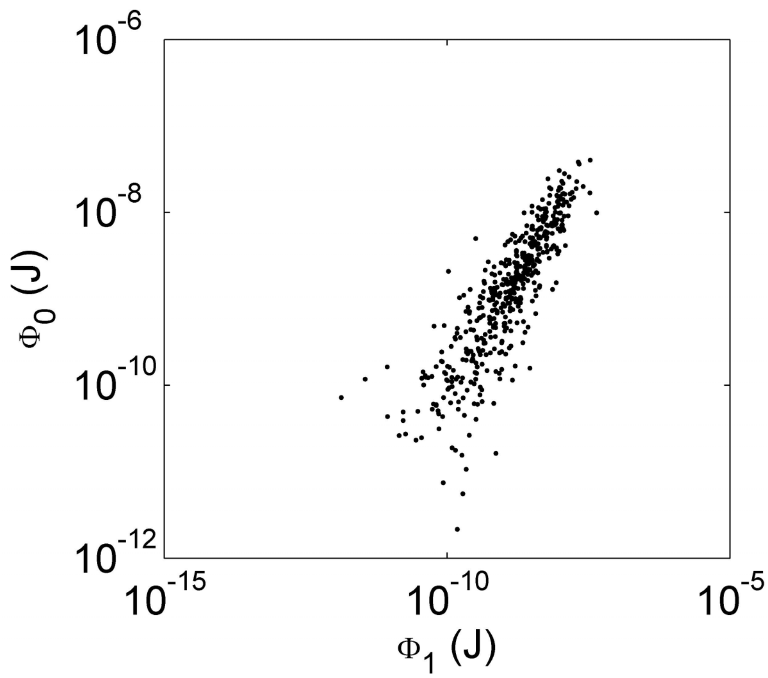

Figure 1.

The evidence for a common excitation mechanism, and the implication that surface tension energy is involved, motivated a study of the acoustic excitation of bubbles released from a nozzle. This simple system provided a regular stream of reproducible events that could be studied in detail with high speed photographic techniques. These experiments were done in collaboration with Dr. Helen Czerski, who is an expert in high-speed photographic techniques from the Cavendish Laboratory, Cambridge. The result of this study was the conclusion that acoustic excitation is driven by the collapse of the remnant neck of air formed immediately after fragmentation. The mechanism is illustrated in Fig. 2, which shows the collapse of a neck fragment and the simultaneous acoustic radiation of a bubble released from a nozzle.

A simple model of the neck based on a balance between surface tension and kinetic energies was able to account for the dynamics of the collapse, which is illustrated in Fig. 3.

Figure 2. Simultaneous views of the pressure trace and the collapsing neck remnant for a bubble released from a nozzle. The roman numerals on the pressure trace annotate the time of the three images along the bottom. The third image shows the formation of a fluid jet within the collapsing neck of air and interface capillary waves radiating away from the collapse region. The acoustic pressure trace is in arbitrary units because the measurements were made in a small, reverberant chamber. Data from bubbles released from a nozzle in reverberation-free conditions show that the peak pressure is between 0.1 to 0.2 pa for the approximately 2 mm radius bubbles studied.

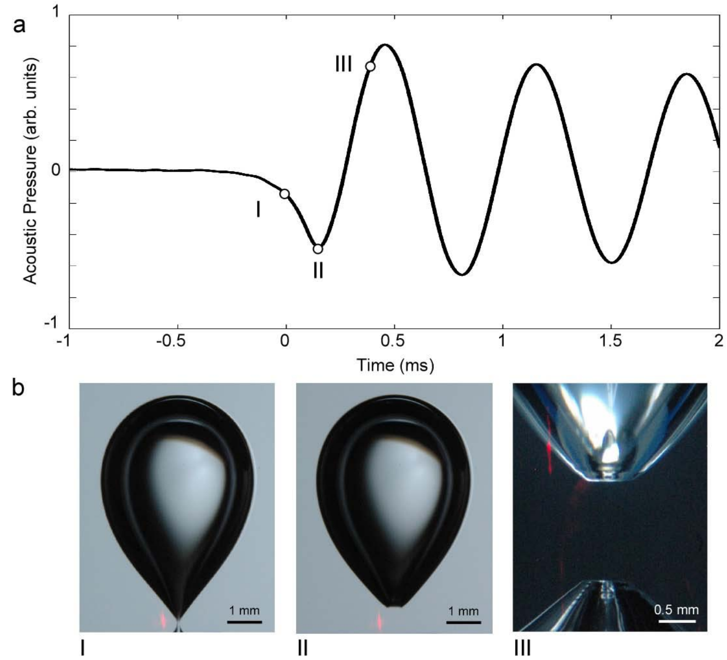

Figure 2

Figure 3. The velocity and travel time of the end of the neck remnant as a function of distance from the neck rupture point. **a**, the circles and squares respectively show fresh and salt water velocity measurements. The solid line is a prediction of the velocity based on the balance of surface tension energy and kinetic energy in a frustum of neck. The overall agreement is within a factor of 2. **b**, travel time of the neck remnant versus time from fragmentation for fresh (circles) and salt water (squares) measurements. The solid line is the theoretical prediction. The theory does not account for any loss mechanisms, and does not capture the deceleration evident in the data after 0.8 ms.

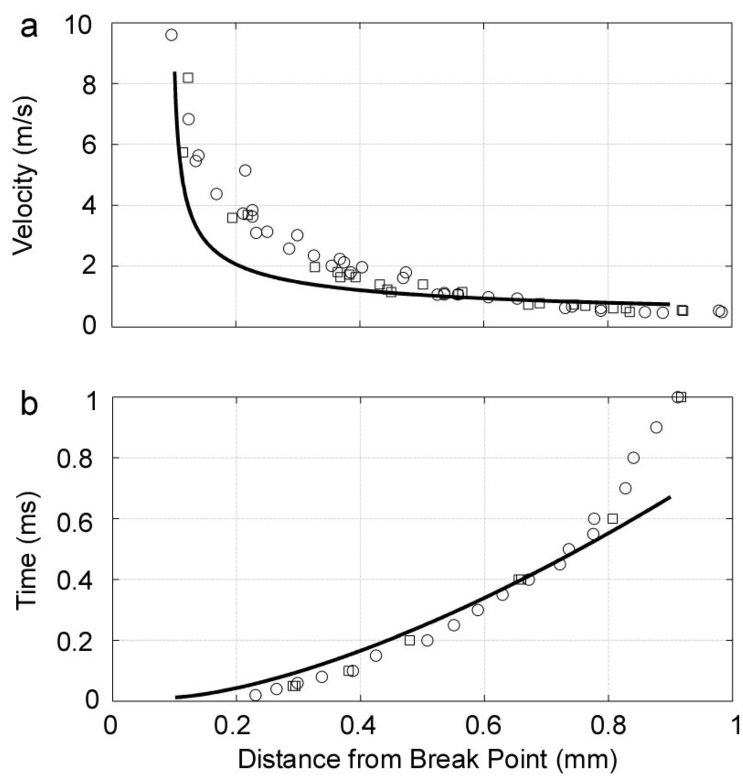

Figure 3

When the model for the collapsing neck is incorporated into the linearized Rayleigh-Plesset equation, it is able to account for the observed amplitude of the breathing mode oscillations driving acoustic emission.

2. The effects of environmental variability on whitecap coverage (see Fig. 4).

Figure 4. Whitecap coverage measured off the air-sea interaction tower at the Martha's Vineyard cabled observatory during the winter of 2002. The whitecap coverage was determined by computer analysis of over 100,000 images of the ocean surface taken during SPACE02. The different symbols correspond to different environmental effects (tides, mixed and swell-dominated seas).

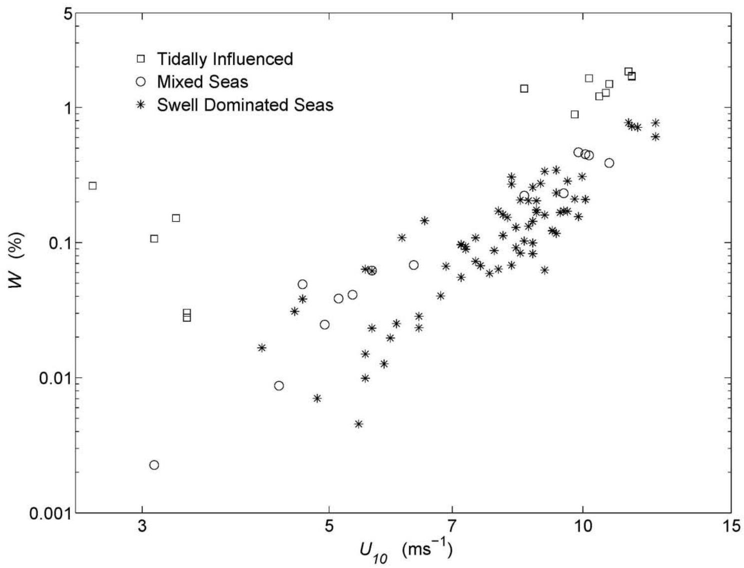

Figure 4

This study, performed by Dr. Adrian Callaghan visiting from the National University of Ireland, Galway, demonstrated the importance of fetch, tidal currents and wave field characteristics in determining whitecap coverage in coastal regions. The tidally-influenced values (the squares in Fig. 4) show whitecap coverage values factors of 2 to 100 greater than what would be expected based on wind speed alone. Swell-dominated seas tended to show more scatter in whitecap coverage than mixed seas.

4. Vector Sensor Deployment.

Figure 4. Underwater photograph of the vector sensor on its support frame. The sensor is suspended from a horizontal support beam with monofilament and stabilized with a lead weight attached approximately 0.5 m below the sensor. The underwater housings on the lower right contain signal conditioning electronics and acquisition computers. The computer systems are attached to an underwater node approximately 40 m to the northwest of the SIO pier, which supplies communications and power connections.

Figure 5

IMPACT/APPLICATIONS

Identifying the excitation mechanism for bubble radiation has a number of implications for understanding origin of breaking wave noise, and using wave noise to estimate the creation rate of bubbles at the ocean surface. The laboratory and field studies of wave focusing have implications for the development of front-end equalizers for underwater modems, and these are being pursued by Dr. James Preisig at the Woods Hole Oceanographic Institution.

RELATED PROJECTS

"Underwater Acoustic Propagation and Communications: A Coupled Research Program", funded under the Multidisciplinary University Research Initiative (MURI) by ONR.

PUBLICATIONS

Callaghan, A.H., Deane, G.B., and Stokes, M.D., "Observed physical and environmental causes of scatter in whitecap coverage values in a fetch limited coastal ocean," JGR [in press, refereed].

Deane, G.B. and Stokes, M.D., "The acoustic emissions and energetics of fragmenting bubbles," J. Acoust. Soc. Am. [submitted].

Deane, G.B. and Czerski, H., "On the origin of bubble noise", *Science*, [submitted].